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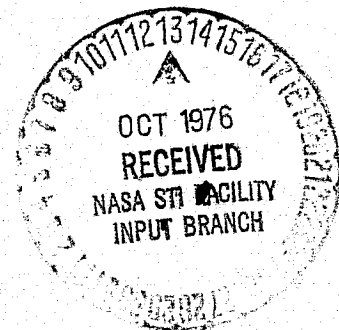
THE WAVELENGTH DEPENDENCE AND AN INTERPRETATION

OF THE PHOTOMETRIC PARAMETERS OF MARS

W. R. Weaver and W. E. Meador
Langley Research Center

September 1976

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1. Report No. NASA TM X-73937	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle THE WAVELENGTH DEPENDENCE AND AN INTERPRETATION OF THE PHOTOMETRIC PARAMETERS OF MARS		5. Report Date September 1976
		6. Performing Organization Code 64.600
7. Author(s) W. R. Weaver and W. E. Meador		8. Performing Organization Report No. NASA TM X-73937
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 185-50-51-01
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

Interim technical information release, subject to possible revision and/or later formal publication.

16. Abstract

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17. Key Words (Suggested by Author(s)) Lunar and Planetary Exploration (Cat. 91) Photometry, Mars, Surface Properties, Remote Sensing, Light Scattering, Diffuse Reflection	18. Distribution Statement Unclassified - Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price* $3.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

The photometric function developed by Meador and Weaver has been used with photometric data from the bright desert areas of Mars to determine the wavelength dependence of the three photometric parameters of that function and to provide some predictions about the physical properties of the surface. Knowledge of the parameters permits the brightness of these areas of Mars to be determined for any scattering geometry over the wavelength range of 0.45 to 0.70 μm. The changes in the photometric parameters with wavelength are shown to be consistent with qualitative theoretical predictions, and the predictions of surface properties are shown to be consistent with conditions that might exist in these regions of Mars. The photometric function is shown to have good potential as a diagnostic tool for the determination of surface properties, and the consistency of the behavior of the photometric parameters is shown to be good support for the validity of the photometric function.

INTRODUCTION

The photometric function developed by Meador and Weaver (ref. 1) is an attempt to describe the full effects of multiple scattering, an improved treatment of particle shadowing, and parameters that qualitatively relate to such physical properties of the scattering surface as particle size, surface compactness, and single particle albedo. The function can be used to extrapolate

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limited brightness measurements to all scattering geometries and to deduce planetary surface texture from remote photometric data, a task that was previously impossible because of the strictly empirical nature of the existing photometric theories. The function has been verified by numerous measurements on laboratory samples, but its wavelength dependence has not been determined. That the photometric behavior of particulate surfaces can be a strong function of wavelength has been found by many investigators (see, for example, refs. 2 and 3); therefore, before multispectral data can be properly analyzed, the wavelength dependence of the photometric parameters of reference 1 must be determined. If the wavelength behavior of the parameters follows the theoretical predictions, it will lend support to the validity of the photometric function and the physical interpretation of the parameters.

The purpose of this paper is, therefore, twofold: to determine the wavelength dependence of the photometric parameters for the planet Mars to facilitate the use of the function in the operation of the Viking Lander cameras and in the analysis of the multispectral photometric data to be returned by the Viking Lander; and to determine if the physical properties of the surface of Mars as predicted by the wavelength dependence of the parameters are consistent with theoretical predictions, thereby further supporting the validity of the photometric function and the physical interpretation of the parameters.

SYMBOLS

a_0	photometric parameter in phase function
a_1	photometric parameter
a_2	packing factor, $n\rho^3$
B	parameter in equation (6)

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C	parameter in equation (16)
C_1, C_2	coefficients in equation (17)
C_3, C_4, C_5	coefficients in equation (18)
f	shadowing-correction factor
G	function defined by equation (11)
H	function defined by equation (10)
i	incident angle with respect to surface normal of impinging collimated radiation
J_1	function defined by equation (12)
J_2	function defined by equation (13)
k	Minnaert exponent
k_0, k_1, k_2, k_3	coefficients in equation (15)
n	particle number density
p	phase function
x	integration variable (see eq. (2))
α	phase angle between direction of incidence and emission
δ	angular deviation from mirror-point geometry (see eq. (8))
ε	emission angle with respect to surface normal of observed scattered radiation
λ	wavelength
μ	function defined by equation (3)
ν	function defined by equation (4)
ρ	effective particle radius
Φ	surface brightness normalized to unity at $i = \varepsilon = 0$
ϕ	azimuthal angle between the planes of incidence and emission

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THE PHOTOMETRIC FUNCTION

The Meador-Weaver photometric function is an attempt to develop a function that is grounded in physical principles, that describes both single- and multiple   processes in diffuse reflection of solar radiation, that includes a more accurate treatment of particle shadowing which contributes to the planetary opposition effect, and that gives information about such physical properties of the surface as particle size, single-particle albedo, and compactness.

The function as given in reference 1 is

$$\Phi(i,\varepsilon,\alpha) = \frac{\cos i}{(1 + a_0 + a_1)(\cos i + \cos \varepsilon)}$$

$$\times \left[(1 + a_0 \cos \alpha) \, f(i,\varepsilon,\alpha,a_2) + a_1(\cos i + \cos \varepsilon)\right] \qquad (1)$$

where Φ is the brightness (normalized to unity at $i = \varepsilon = 0$); i is the angle of incidence; ε is the angle of emission; α is the phase angle; and a_0, a_1, and a_2 are semiempirical parameters that contain information about the surface. The factor f is the shadowing-correction factor and is given by

$$f(i,\varepsilon,\alpha,a_2) = e^{\mu-\nu} + \nu \int_0^1 \exp\left\{\mu - \frac{\nu}{6\pi}\left[3\pi x + 2(2 + x^2)(1 - x^2)^{1/2}\right.\right.$$

$$\left.\left. + 6x \sin^{-1}x\right]\right\} dx \qquad (2)$$

where

$$\mu = \frac{4a_2(1 + \cos \alpha)}{3 \sin \alpha} \qquad (3)$$

$$\nu = \frac{\pi a_2(\cos i + \cos \varepsilon)}{\sin \alpha \cos i \cos \varepsilon}\left[\sin^2\alpha + 2(1 + \cos \alpha) \cos i \cos \varepsilon\right]^{1/2} \qquad (4)$$

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$$\cos \alpha = \cos i \cos \epsilon + \sin i \sin \epsilon \cos \phi \tag{5}$$

and ϕ is the azimuthal angle between the planes of incidence and emission.

As noted in reference 1, equation (2) approaches an incorrect limit at grazing incidence or emission. This behavior has been found to be the result of an inadequate theoretical treatment of the particles in the surface layer (ref. 4) and can be partially corrected by simply using equation (2) for all scattering geometries for which f exceeds unity and by replacing equation (2) with $f = 1$ for larger values of i or ϵ. The complete normalized photometric function is then the combination of equation (1) with the shadowing-correction factor of equation (2) and its correction when f is less than unity.

ANALYSIS PROCEDURES

The semiempirical parameters a_0, a_1, and a_2 contain the wavelength dependence of equation (1) and appear in such a complex way that it was necessary to resort to an iterative procedure for their determination. The development of the procedure was influenced by the wide use of the Minnaert photometric function and the presentation of planetary photometric data in a form compatable with that function. The Minnaert function is

$$\Phi(i,\epsilon,\alpha) = B(\alpha)(\cos i)^k (\cos \epsilon)^{k-1} \tag{6}$$

where Φ is the brightness, k is the Minnaert exponent, and $B(\alpha)$ is the brightness at zero phase angle. Planetary brightness data are usually given in the form of Minnaert plots (fixed α) in which $\ell n(\Phi \cos \epsilon)$ is plotted against $\ell n(\cos i \cos \epsilon)$. The slope of the linear portion of the plot is, thus, the value of the exponent k.

The iterative procedure used in the determination of the values of the three photometric parameters makes use of the fact that for certain geometries the Minnaert function is a good approximation to the Meador-Weaver function (ref. 1). For example, Minnaert plots of equation (1) yield straight lines starting at and continuing for some distance from the mirror-point geometry defined by $i = \varepsilon$. The slope k of this linear portion of a Minnaert plot is obtained from

$$k(\alpha) = \lim_{\delta \to 0} \left\{ \frac{d\left[\log_e (\Phi \cos \varepsilon)\right]}{d\left[\log_e (\cos i \cos \varepsilon)\right]} \right\}_{\alpha = \text{constant}} \tag{7}$$

where δ is the angular deviation from the mirror-point geometry (equal incident and emission angles on opposite sides of the surface normal) and is given by the equation

$$\delta = i - \frac{\alpha}{2} = \frac{\alpha}{2} - \varepsilon \tag{8}$$

Evaluation of equation (7) using the definition of equation (8) yields

$$k(\alpha) \approx 1 - \frac{1}{2} \cos^2 \frac{\alpha}{2} - \frac{p(\alpha) H(\alpha) - a_1 \cos(\alpha/2)}{p(\alpha) G(\alpha) + 2a_1 \cos(\alpha/2)} \cos^2(\alpha/2) \tag{9}$$

where

$$H(\alpha) = \frac{4\pi a_2 \tan^2(\alpha/2)}{\sin \alpha} \left\{ J_1(\alpha) - \exp\left[\frac{4a_2(1 - 3\pi + \cos \alpha)}{3 \sin \alpha}\right] \right\} \tag{10}$$

$$G(\alpha) = \frac{4\pi a_2}{\sin \alpha} J_2(\alpha) + \exp\left[\frac{4a_2(1 - 3\pi + \cos \alpha)}{3 \sin \alpha}\right] \tag{11}$$

$$J_1(\alpha) = J_2(\alpha) - \frac{2a_2}{3 \sin \alpha} \int_0^1 \left[3\pi x + 6x \sin^{-1} x + 2(2 + x^2)(1 - x^2)^{1/2} \right]$$

$$\times \exp\left\{ \frac{2a_2}{3 \sin \alpha} \left[2 + 2 \cos \alpha - 3\pi x - 6x \sin^{-1} x - 2(2 + x^2)(1 - x^2)^{1/2} \right] \right\} dx \tag{12}$$

$$J_2(\alpha) = \int_0^1 \exp\left\{\frac{2a_2}{3\sin\alpha}\left[2 + 2\cos\alpha - 3\pi x - 6x\sin^{-1}x - 2(2 + x^2)(1 - x^2)^{1/2}\right]\right\}dx$$

(13)

and $p(\alpha)$ is the linear anisotropic phase function defined as

$$p(\alpha) = 1 + a_0\cos\alpha.$$

(14)

The iterative procedure is as follows:

1. For a given value of phase angle, a Minnaert plot of brightness data is constructed and the slope k of the linear portion of the data near the mirror geometry is determined.

2. The preceding step is repeated for a range of phase angles sufficient to define the slope k as a function of the phase angle.

3. Choose a $k(\alpha_1)$ and a $k(\alpha_2)$ away from the midpoint and the extremes of the range of phase angle and use with equation (9) to determine the value of a_2 that forces $a_1(\alpha_1) = a_1(\alpha_2)$. This is repeated for enough assumed values of a_0 between its maximum value of $+1$ and its minimum value of -1 to define a_1 and a_2 as functions of a_0.

It might seem that the sets of a_0, a_1, and a_2 determined in this way could be used to compare equation (9) to the $k(\alpha)$ data of step 2 to determine which set forces a match. This comparison, however, is found to be too insensitive to determine the three parameters without considerable ambiguity. It is necessary, therefore, to use something other than k for comparison purposes.

A comparison that is sensitive enough is that between equation (1) and the brightness data of step 1 for a particular geometry for which sufficient data exists. This comparison proceeds as follows:

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4. The sets of parameters determined in step 3 are used with equation (1) and compared to the brightness data used in step 1 for a particular geometry, for example, $\varepsilon = 0$ (normal emission). Since the brightness data and equation (1) are in general not tied to a single calibration standard, it is necessary to normalize the brightness data at some midrange value of phase angle to match the values from equation (1).

5. Step 4 is repeated until equation (1) matches the brightness data. The set of photometric parameters used with equation (1) to obtain the match is, thus, the set unique to that data.

This procedure was successfully used in reference 1 to evaluate the photometric parameters for four basaltic materials. There it was shown that steps 1 through 5 do not bias the results toward the two particular geometries used to obtain the parameters because the parameters adequately predicted the brightness of the materials for a third, quite different geometry: i fixed, while ε was varied over its entire range.

THE DATA

Two sets of Earth-based photometric measurements of the bright desert regions of Mars were used to evaluate the photometric parameters of equation (1). One is the compilation of brightness data as a function of wavelength that formed one of the bases for the photometric function of reference 5 and represents the results of a number of earlier investigations. The other is the set of variations of the Minnaert exponent k with phase angle and wavelength contained in reference 2. None of the earlier Mariner 6 and 7 data were used because of the restriction of the far-encounter measurements to a single phase angle. Also, none of the Mariner 9 photometric measurements could be used because they are restricted to a single, narrow band of wavelengths.

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Since the data of both reference 2 and reference 5 refer to scattering geometries for which the Minnaert function is valid and since the data are presented in that form, the techniques of the preceding section are directly applicable. For the first part of the iterative procedure, results of reference 2 are considered more reliable than those of reference 5 because the values of k were obtained directly from the slopes of Minnaert plots, whereas the data used by reference 5 admittedly contain a number of arbitrary and unjustified assumptions about the behavior of k. The results of reference 2 are not completely reliable, though, because of large experimental scatter, uncertainties in the measurements, and insufficient data to definitely establish the exact dependence of k on phase angle and wavelength. It was also necessary to correct figure 3 of reference 2 because the data for the phase angles 17.7° and 18.5° had been plotted incorrectly. The brightness data of reference 5 were considered reliable for the latter part of the iterative procedure because they are based on direct observations and are thus independent of the arbitrary assumptions about the individual behavior of the Minnaert coefficient and exponent.

DETERMINATION OF PHOTOMETRIC PARAMETERS

The variation of k with the phase angle was determined from reference 2 by the construction of a function that fitted the raw data for a wavelength of 0.605 μm and the refined data for the phase angles 10.3° and 17.7°. The function is

$$k(\alpha,\lambda) = k_0 + \frac{k_1}{\lambda} + (k_2 + \frac{k_3}{\lambda})\alpha \tag{15}$$

where λ is the wavelength in μm, α is the phase angle in radians, and $k_0 = 5.158 \times 10^{-1}$, $k_1 = -7.960 \times 10^{-3}$, $k_2 = 1.674$, and $k_3 = -5.342 \times 10^{-1}$.

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Figure 1 shows the variation of k with phase angle for $\lambda = 0.605$ µm and the linear regression curve used to correlate the data. Note that the two data points for the larger values of phase angle were plotted incorrectly in the original reference. The corrected values used here are from reference 6. Equation (15) was used in step 3 of the iterative procedure to determine the values of a_1 and a_2 for the range of a_0.

The brightness data of reference 5 are given in the form of a Minnaert function as

$$\Phi(i,\varepsilon,\alpha,\lambda) = C(\alpha,\lambda)(\cos i)^{k(\alpha,\lambda)}(\cos \varepsilon)^{k(\alpha,\lambda)-1} \tag{16}$$

where

$$k(\alpha,\lambda) = 0.475 + 0.375\lambda + C_1\alpha + C_2\alpha^2 \tag{17}$$

$$C(\alpha,\lambda) = 0.621 + 0.238\lambda + (C_3 + C_4\lambda)(C_5\alpha + \alpha^2) \tag{18}$$

with $C_1 = 0.0117576$, $C_2 = -7.1311 \times 10^{-5}$, $C_3 = 1.4528 \times 10^{-4}$, $C_4 = -1.5227 \times 10^{-4}$, $C_5 = -96.4273$ and α in degrees.

Equation (6) was used in steps 4 and 5 of the iterative procedure to determine a_0, a_1, and a_2 from comparisons with equation (1). Figure 2 is an example for $\lambda = 0.55$ µm of the overall ability of equation (1) to match the brightness data of reference 5. In evaluating figure 2 it should be recalled that a different data set (namely, that of ref. 2) was used in the first three steps of the iterative procedure and resulted in a particular grouping of the photometric parameters that directly affects the ability of equation (1) to fit the data of reference 5. That the match in figure 2 is reasonably good can be an indication of a basic compatability between the two data sets. In determining the criteria for a match in the comparisons, of which figure 2 is an

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example, the brightness data at phase angles greater than about 60° were given less weight because of the inaccuracies that might exist because of the failure of equation (2) to approach a proper limit at grazing incidence.

The numerical values of the three photometric parameters as a function of wavelength are given in table I for the range 0.45 to 0.70 μm. Figures 3, 4, and 5 graphically show the variation of a_0, a_1, and a_2 with wavelength together with third-order polynomials to correlate the data. The coefficients of the polynomials are given in table II to facilitate numerical generation of the data.

PHYSICAL INTERPRETATION OF PARAMETERS

The photometric function used herein was developed not only to provide a more accurate extrapolation of limited brightness data to arbitrary geometries, but also to provide a means to make quantitative interpretations about the physical properties of the surface material. The photometric parameters indeed do have physical meaning, as will be evident from the following discussion; however, it is also evident from the discussion that further theoretical and experimental evaluation of the precise meaning of the parameters is needed. At present, therefore, the parameters can only be considered to give qualitative predictions of the physical properties of the surface. It should be emphasized that the physical properties determined from photometry apply only to the layer of surface material that contributes to the scattering process--in the case of visible radiation, probably a depth of only a few particle diameters.

The determination of a_0 from experimental data should yield information on mean particle size through the relation of that property to the particle transparency if large particles of the same material are opaque. This condition

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should be applicable to much of the sandy desert material of Mars since it is thought (ref. 7) to be mostly feldspar, mafic minerals, and basalt fragments, not quartz. The parameter a_0 is limited to values between -1 and +1 where an excess of forward scattering, as could occur by means of transmission through small particles, is indicated by negative values; isotropic scattering is indicated by a value of zero, and an excess of backscattering is indicated by positive values. The parameter a_1 is proportional to the ratio of multiple to single scattering and, thus, relates to the single particle albedo. The limits of a_1 are zero and infinity, corresponding, respectively, to the limit of very dark, single-scattering materials to the limit of very bright, Lambert surfaces. The parameter a_2 is the packing factor and is given in its simplest form by the equation

$$a_2 = n\rho^3 \tag{19}$$

where n is the particle number density and ρ is the effective particle radius. The packing factor can have values between zero and unity where the smaller the value the more porous the structure of the surface.

RESULTS

Because of the complex interrelationships of the photometric parameters with each other and with particle size and wavelength, the delineation of the results and how they in turn support the validity of the photometric function will proceed as follows: the results will first be stated, then followed by a discussion of the variation of the parameters with particle size and, lastly, by a discussion of their variation with wavelength. When analyzed by the techniques of the preceding sections, photometric data of the bright desert areas of Mars yield photometric parameters that correspond to a surface that has a mean particle size of about 125 μm, or possibly smaller, and allows forward scattering to

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dominate, reflects light with low orders of multiple scattering, and has a tightly packed structure with low porosity.

The interpretation of the values of the photometric parameters is made more meaningful when the values are compared with those measured for other materials in the laboratory. Table III gives the results of measurements from reference 1 on two size ranges of each of two different basaltic materials. Note that for each material, as the size of the laboratory materials increases, the value of a_0 increases. This is consistent with the concept of a_0 as a measure of particle size through its relation to the increased transparency of particles as size decreases. The parameter a_1, since it is a measure of the amount of multiple scattering, should increase as the particle size decreases. This is the behavior found in table III and occurs because some of the radiation that would be absorbed by the larger particles is transmitted through the smaller ones to be scattered again and partially to emerge as reflected light. This behavior corresponds to the observation that, for sufficiently small particles, surfaces generally become brighter as the particle size is diminished. The packing factor a_2 is seen from table III to increase with a decrease in particle size to imply a less porous structure for the small particle surfaces and a correspondingly smaller opposition effect. That the values of a_2 in table III can exceed the geometrical limit of 0.125 is explained in reference 1 in terms of strong diffraction which probably causes ρ of equation (19) to exceed the mean particle radius and, thereby, increases the value of a_2. More specifically, the behavior of a_2 with particle size results from the smaller apertures between the particles of the small-particle samples; these smaller apertures between particles cause greater diffraction of the light passing through these apertures and, thus, corresponds to an increase in the apparent packing of the surface as deduced from photometry.

The wavelength dependence of the photometric parameters for Mars as derived by the methods of this paper are given in table I. The values of a_0 are large and negative ranging from -0.34 at $\lambda = 0.45$ μm to -0.71 at $\lambda = 0.70$ μm and indicate that the particles are sufficiently small that forward scattering predominates. If the material on the surface of Mars has values of permittivity, permeability, and electrical conductivity that are not too different from those of the laboratory materials of table III, then the large negative values of a_0 imply a mean particle size about the same as or smaller than 125 μm. That reference 6 finds a mean particle size considerably larger than this may result from the fact that reference 6 used data integrated over the entire planet, excluding the poles, while the data used herein applies only to the bright desert areas where aeolian forces could effect a considerably smaller mean particle size than might be expected in the nondesert area of Mars. The variation of a_0 with wavelength indicates the expected increase in material transparency at longer wavelengths, thus, supporting the validity of the photometric function and the physical interpretation of a_0.

The small values of a_1 in table I indicate that the radiation reflected from Mars has undergone little multiple scattering. If it is assumed that penetration of the particulate surface by the radiation is necessary to produce multiple scattering and if, as the values of a_0 suggest, the mean particle size is small, there may be substantial numbers of very small particles in the surface layer that fill the spaces between the larger particles and result in insufficient penetration of the surface material to permit significant multiple scattering to occur. The increase in the value of a_1 with wavelength, as given in table I, is consistent with the variation of a_0 since the increased

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transmission (as wavelength increases) that is implied by a_0 would lead to increased multiple scattering.

Since the values of a_2 in table I are much larger than those for the laboratory materials of table III and since the value of a_2 for each laboratory material increases with decreasing particle size, the implication is that the mean particle size of the Mars surface material is smaller than the laboratory materials, ·thus supporting the conclusions drawn from the behavior of a_0 and a_1. The large values of a_2 in table I also indicate that the surface of Mars is more tightly packed than were the laboratory surfaces of reference 1 which were formed by air dropping the particulate material from a height of about 0.5 m. That the values of a_2 exceed the geometrical limit can be understood in terms of the strong diffraction discussed earlier in this section; this, when taken together with the increase in the value of a_2 with an increase in wavelength found in table I, offers good support for the contention that diffraction is probably playing a substantial role in the scattering process.

CONCLUDING REMARKS

The photometric function developed by Meador and Weaver has been used with photometric data from the bright desert areas of Mars to determine the wavelength dependence of the three semiempirical parameters of that function and to provide some predictions about the physical properties of the surface of Mars. Knowledge of the parameters permits the brightness of these areas of Mars to be determined for any scattering geometry over the wavelength range of 0.45 to 0.70 µm. The changes in the photometric parameters with wavelength are shown to be consistent with the theoretical interpretations, and the

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surface properties of Mars predicted from the parameters are shown to be consistent with conditions that might exist in those regions of the planet. The prediction of surface properties, however, is not yet quantitative, and in some instances the implications of the results are not well understood. Clearly, more theoretical and experimental work needs to be done before predictions of the physical properties of a surface from the photometric parameters can be considered quantitative. Most important, though, is that the laboratory work of reference 1 which determined some properties of the photometric parameters as functions of particle size, and especially the present analysis which defines their wavelength dependence, offers good support for the validity of the photometric function and clearly shows its potential as a diagnostic tool for the determination of the physical properties of a surface from analyses of the light reflected from that surface.

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TABLE I

WAVELENGTH DEPENDENCE OF PHOTOMETRIC PARAMETERS FOR MARS

λ, μm	a_0	a_1	a_2
.45	-0.34	3.465×10^{-3}	0.6513
.50	-0.48	6.137×10^{-3}	0.8255
.55	-0.56	8.021×10^{-3}	0.9693
.60	-0.62	9.249×10^{-3}	1.0905
.65	-0.68	9.591×10^{-3}	1.1947
.70	-0.71	1.019×10^{-2}	1.2848

TABLE II

COEFFICIENTS FOR 3RD ORDER POLYNOMIAL FIT OF PHOTOMETRIC PARAMETERS FOR MARS

Parameter	λ^0	λ^1	λ^2	λ^3
a_0	4.5590	-21.8419	31.3330	-15.5554
a_1	-0.1069	0.4917	-0.6996	0.3372
a_2	-3.1139	14.4189	-16.7347	7.3051

TABLE III.- PHOTOMETRIC PARAMETERS FOR LABORATORY MATERIALS

(From reference 1)

Material	Mean particle diameter, μm	a_0	a_1	a_2
Colorado basalt (latite)	105	-0.40	0.28	0.32
Colorado basalt (latite)	225	-.10	.26	.15
Basalt dune sand	125	-.10	.25	.17
Basalt dune sand	210	.05	.20	.09

λ = 0.605 μm

Phase angle , α , degrees

Minnaert exponent, k
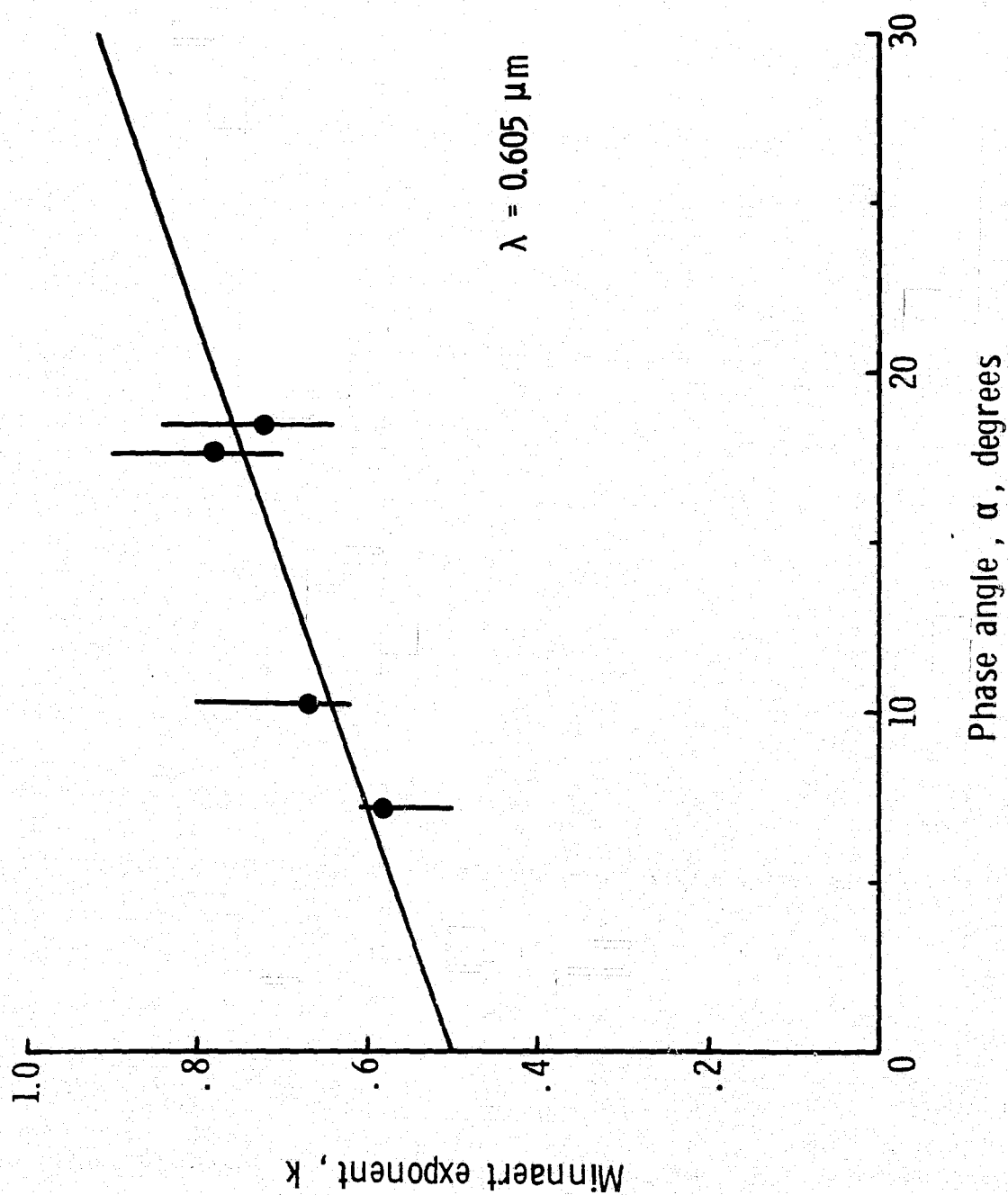
Figure 1.- Minnaert exponent for the bright desert areas of Mars at a wavelength of 0.605 μm (from reference 2). Solid line is linear regression fit to correlate the data.
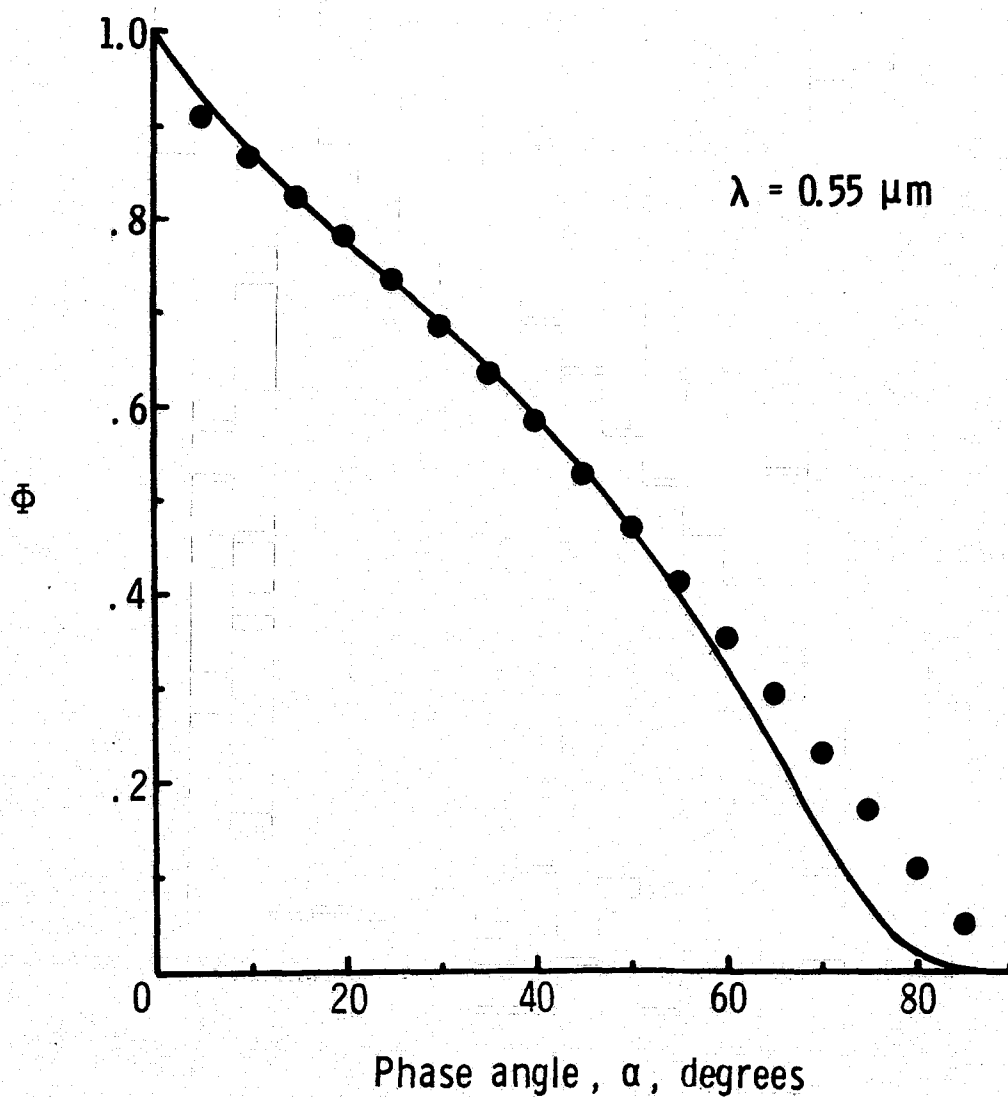
Figure 2.- Normalized brightness for the bright desert areas of
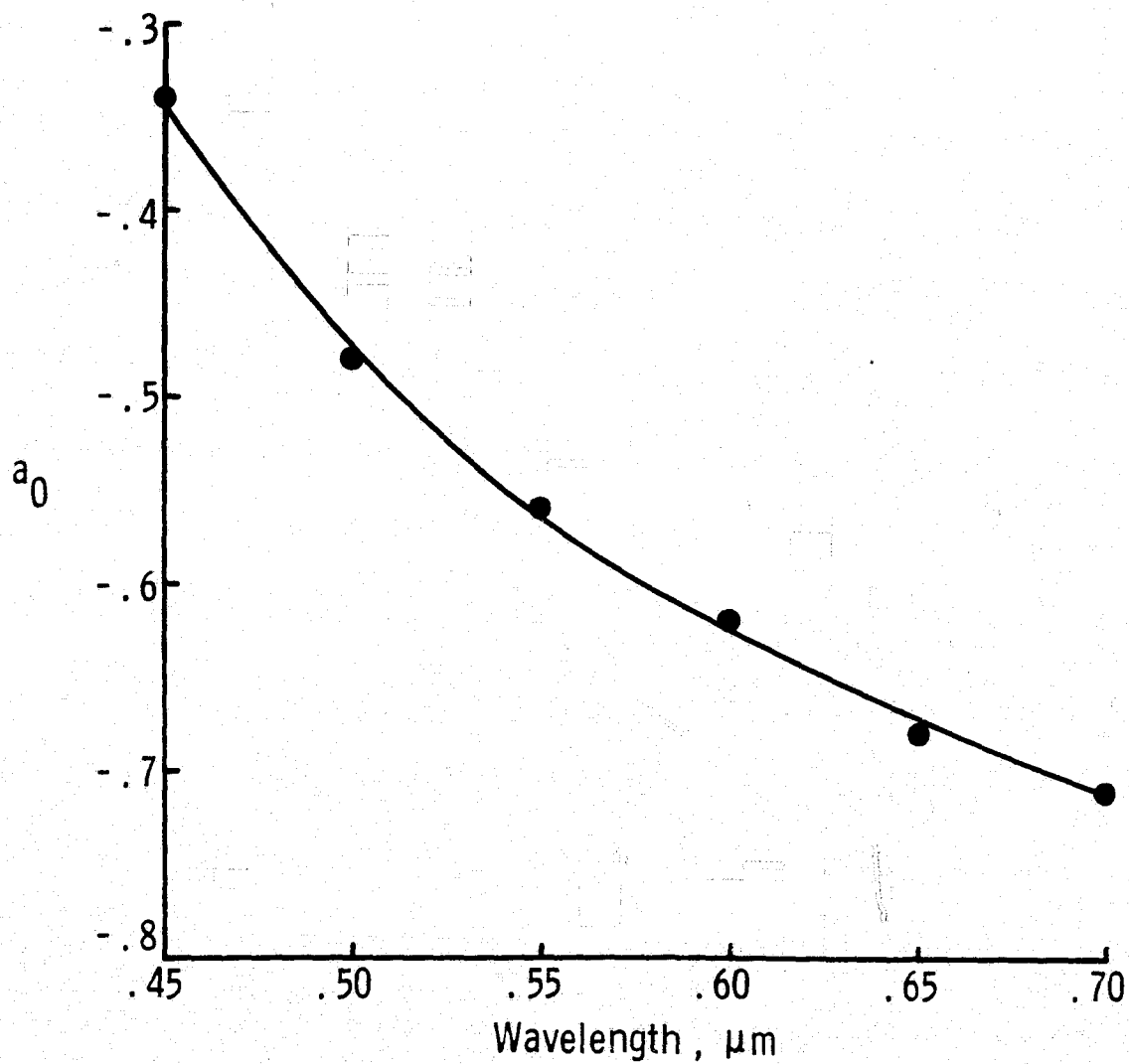Mars at a wavelength of 0.55 μm (from reference 5).
Solid line is equation (1).

Figure 3.- Photometric parameter a_0 of equation (1). Solid line is 3rd order polynomial fit to the data (see Table II for coefficients).
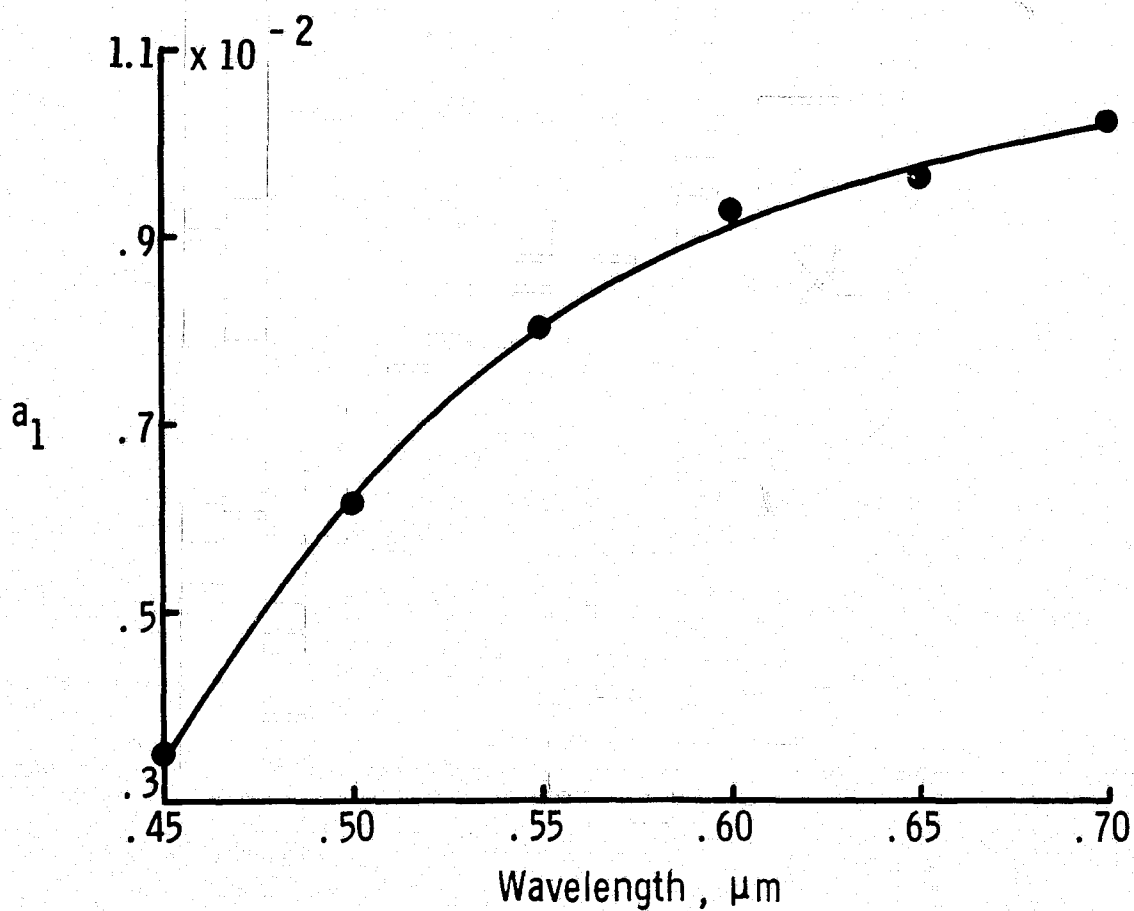
Figure 4.- Photometric parameter a_1 of equation (1). Solid line
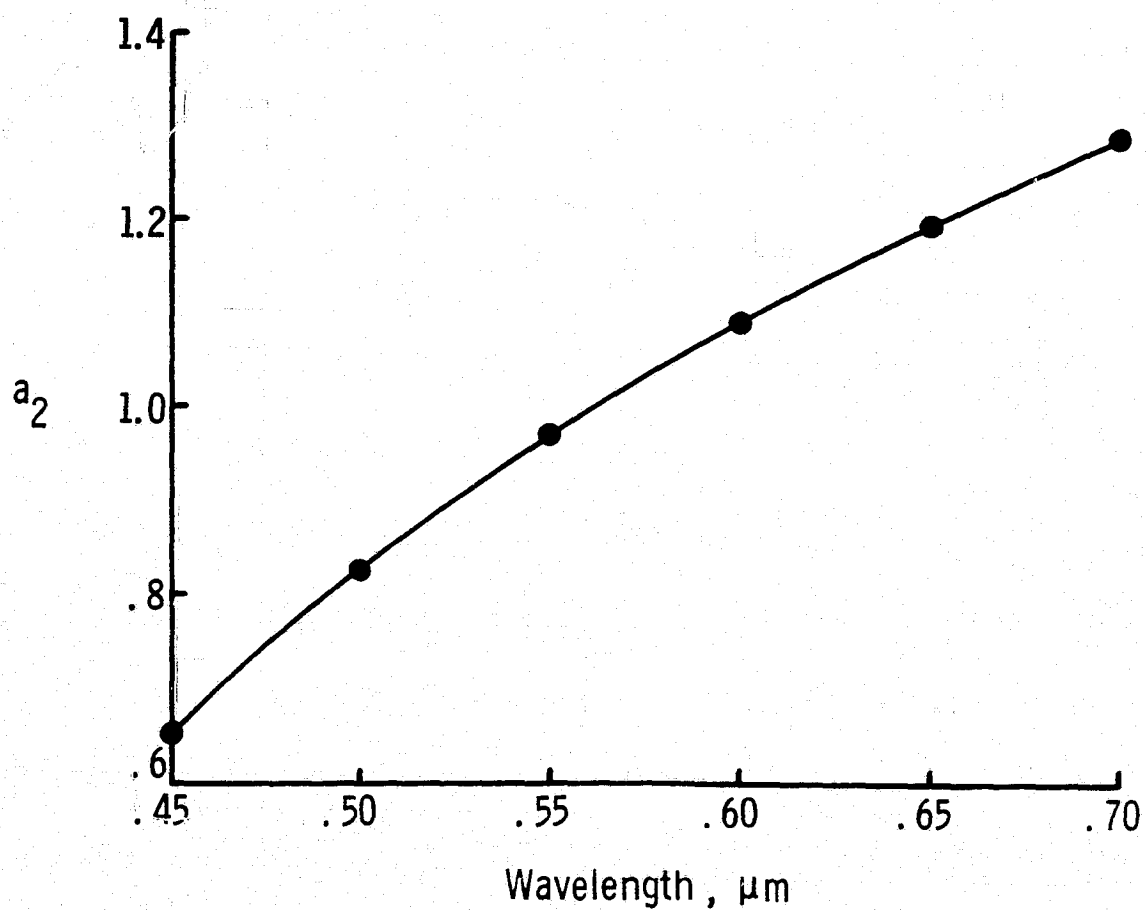is 3rd order polynomial fit to the data (see Table II
for coefficients).

Figure 5.- Photometric parameter a_2 of equation (1). Solid line is 3rd order polynomial fit to the data (see Table II for coefficients).